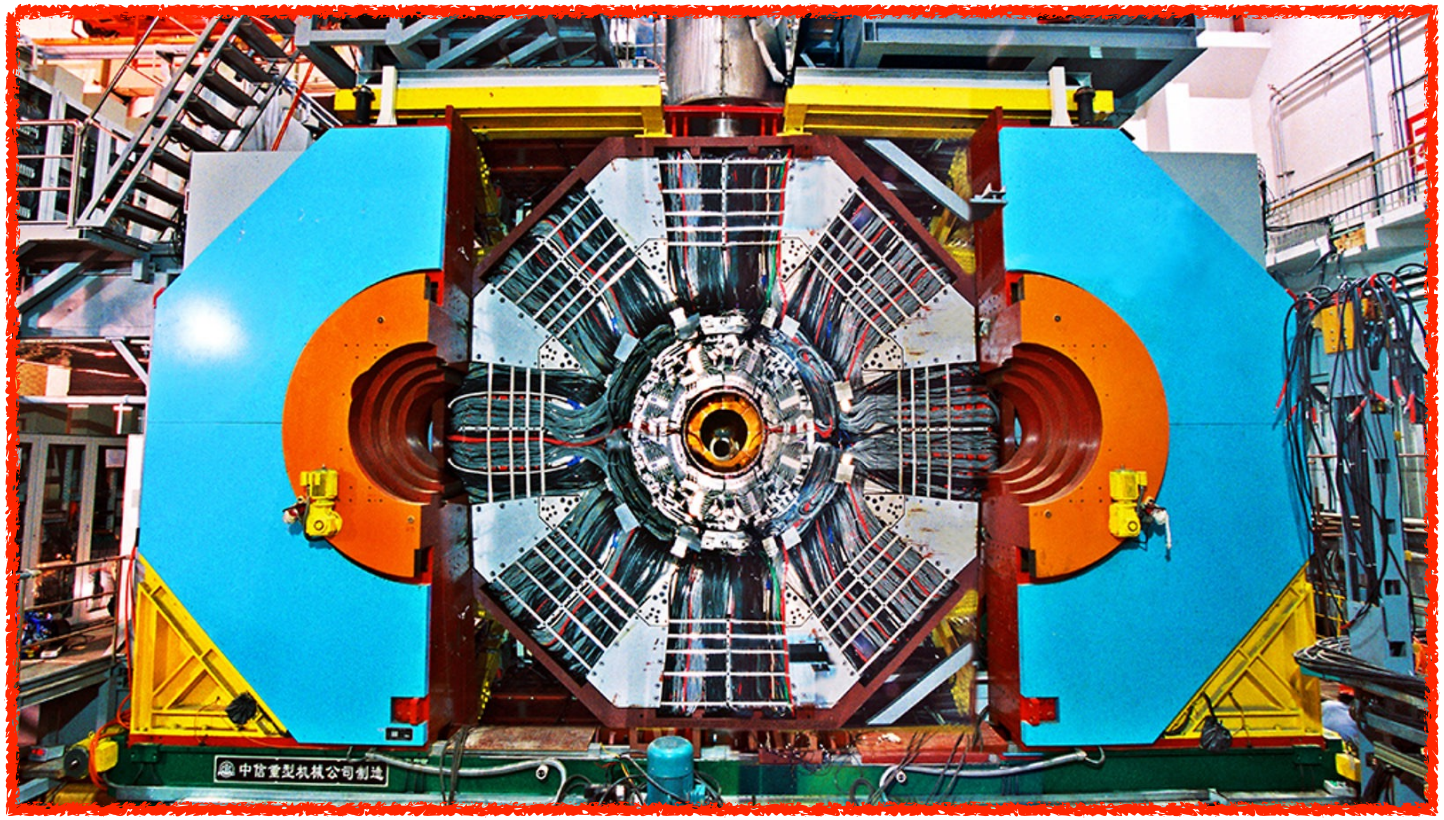
Study of Λ_c decays at BESIII



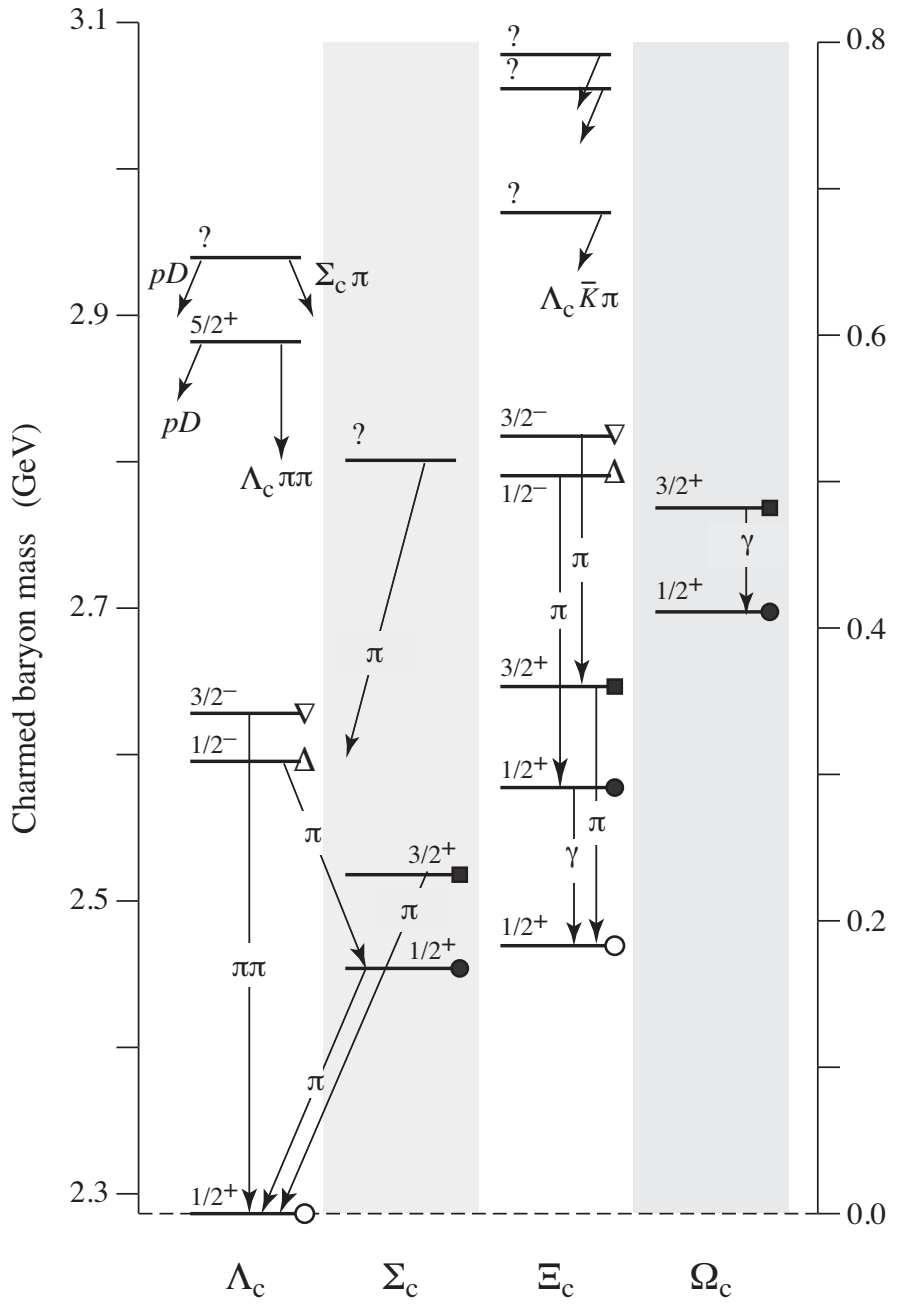
Hajime Muramatsu
University of Minnesota

Measurements that I report today

- BF($\Lambda_c^+ \to p\, K^-\, \pi^+$) : PRL 116, 052001 (2016)
- BF($\Lambda_c^+ \to n\, K_S^0\, \pi^+$) : PRL 118, 12001 (2017)
- BF($\Lambda_c^+ \to p\, (\pi^+\pi^-/K^+K^-)$) : PRL 117, 232002 (2016)
- BF($\Lambda_c^+ \to p\, (\eta/\pi^0)$) : PRD 95, 111102(R) (2017)
- BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$) : just accepted to PLB
- BF($\Lambda_c^+ \to \Lambda\, X$) : Preliminary result
- BF($\Lambda_c^+ \to \Lambda\, e^+\, \nu_\mu$) : PRL 115, 221805 (2015)
- BF($\Lambda_c^+ \to \Lambda\, \mu^+\, \nu_\mu$) : PLB 767, 42 (2017)

Λ_c

- The lightest charmed baryons
  → most of the charmed baryons will eventually decay into Λ_c. Important to know the decay properties of Λ_c.
- The golden mode, $\Lambda_c^+ \to p K^- \pi^+$, often used to normalize many BFs.
  ⇒ Very important to determine the absolute BF.
- Also important input to Λ_b Physics as Λ_b decays dominantly to Λ_c.
- Total known measured BF is ~ 60%.



BESIII is at Institute of High Energy Physics (IHEP) in Beijing, China

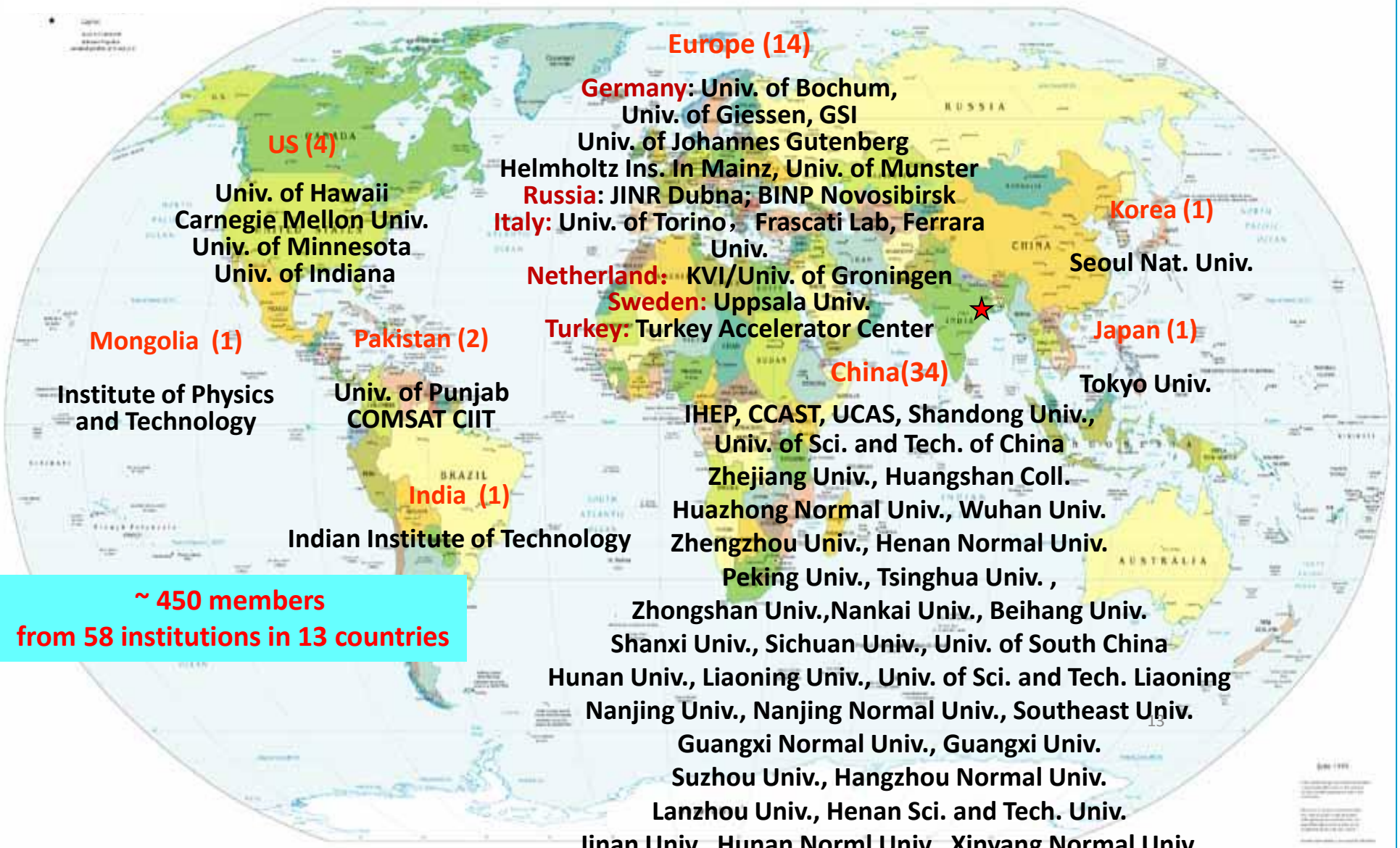
IHEP

Beijing Airport

Beijing Downtown

Map data ©2017 United States Terms Send feedback 2 mi

BESIII Collaboration



Europe (14)

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz, Univ. of Munster
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino, Frascati Lab, Ferrara Univ.
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

US (4)

Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Indiana

Korea (1)

Seoul Nat. Univ.

Mongolia (1)

Institute of Physics and Technology

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

Japan (1)

Tokyo Univ.

China(34)

IHEP, CCAST, UCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ., Beihang Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ., Univ. of Sci. and Tech. Liaoning
Nanjing Univ., Nanjing Normal Univ., Southeast Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Jinan Univ., Hunan Norml Univ., Xinyang Normal Univ.

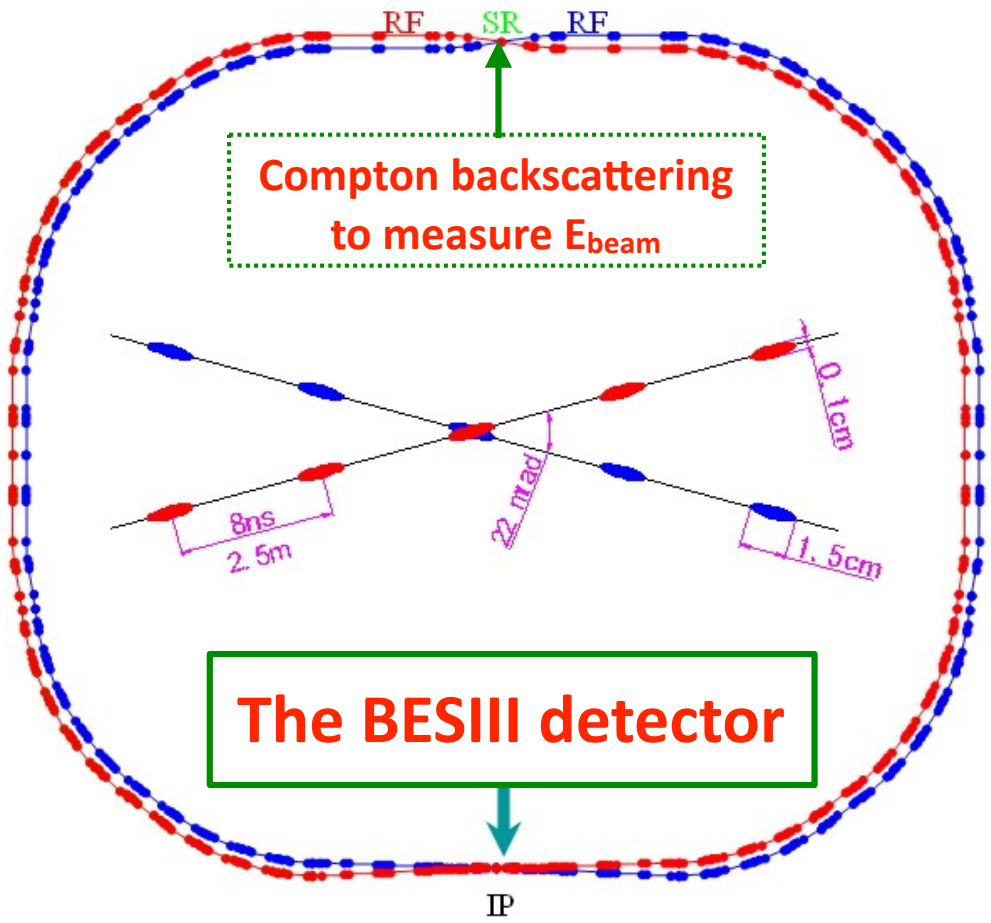
India (1)

Indian Institute of Technology

~ 450 members
from 58 institutions in 13 countries

BEPC II
(Beijing Electron-Positron Collider II)

- Double ring collider.
- Operating since 2008.
- E_{beam} = 1-2.3 GeV.
  Optimal @ 1.89 GeV.



- Can fill up to 93 bunches in each ring w/ max current of 0.9A.
- Designed luminosity = 1×10^{33} $cm^{-2}s^{-1}$ was achieved in April 2016!

BEPC II and BESIII

BESIII detector

- A powerful general purpose detector.
- Excellent neutral/charged particle detection/identification with a large coverage.
  - ✓ Precision tracking
  - ✓ CsI calorimeter
  - ✓ PID via dE/dx & Time of Flight

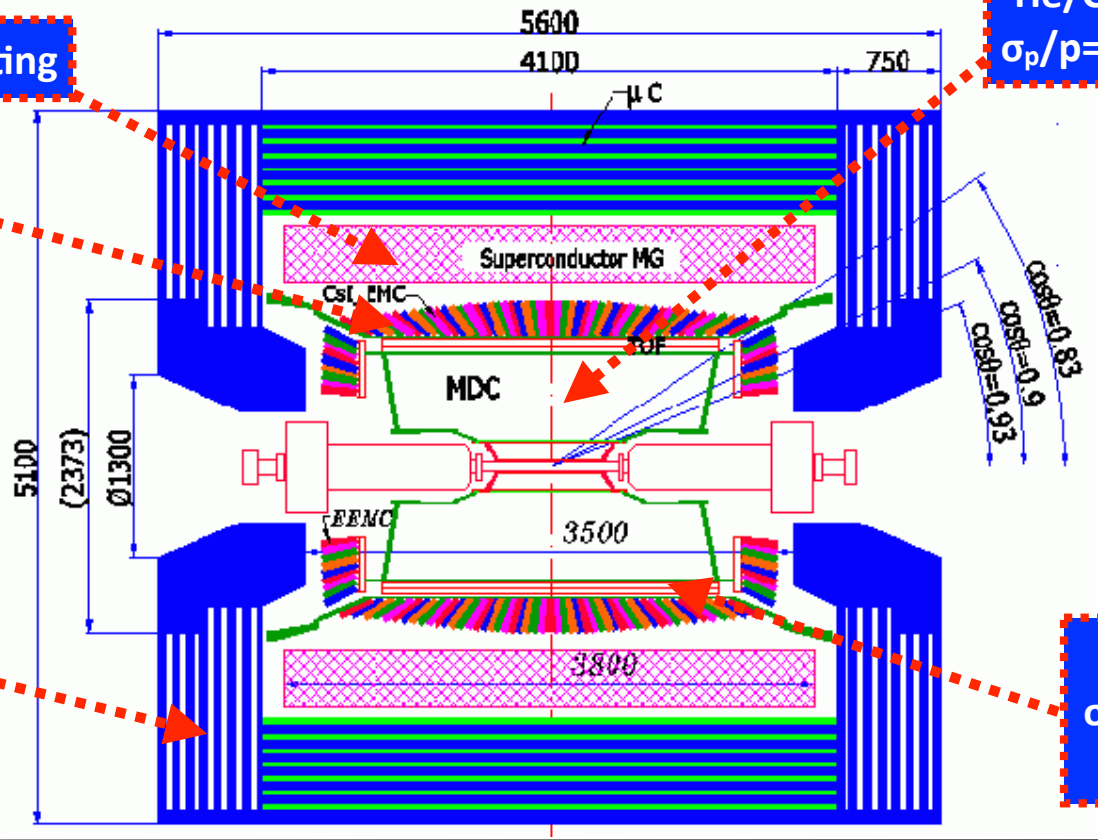
Magnet: 1T Super conducting

EMCAL: CsI crystal
ΔE/E=2.5 @1GeV

MUC: 9 layers RPC
(8 layers in Endcap)
$\sigma_{R\Phi}$=1.4~1.7cm

MDC: small cell & Gas:
He/C_3H_8 (60/40), 43 layers
σ_p/p=0.5%@1GeV, σ_{dEdx}=6%

Time of Flight
σ_T=100ps in Barrel
110ps in Endcap



The e^+e^- annihilation data sample

- Collected at E_{cm} = 4.599 GeV (CPC 40, 063001 (2016)).
  $E_{cm} - 2\times M_{\Lambda c}$ = 26 MeV only!

- The integrated luminosity = 567 pb^{-1} (CPC 39, 093001 (2015)).

- Number of Λ_c produced ~ 0.2M (PRL 116, 052001 (2016)).

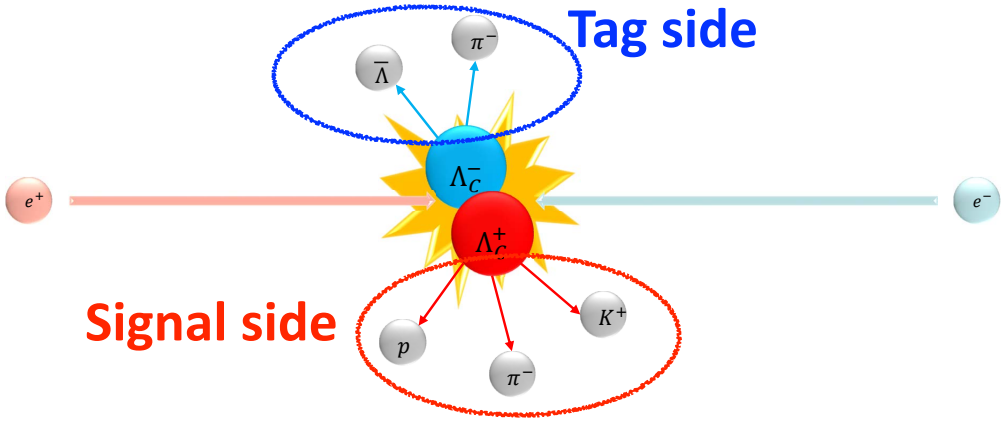
Other CHARM samples

- $D^{0(+)}$ sample: collected at E_{cm} = 3.773 GeV.
  The integrated luminosity = 2.93 fb^{-1}.
- D_s samples:
  - collected at E_{cm} = 4.009 GeV.
    The integrated luminosity = 0.482 fb^{-1}.
  - collected at E_{cm} = 4.178 GeV.
    The integrated luminosity = 3.19 fb^{-1}.

for more details, see;
Bai-Cian Ke's talk ($D_{(s)}$ hadronic decycays; right after this talk)
and
Huijing Li's talk ((semi) leptonic decays of $D_{(s)}$ in
Thursday morning session of Quark and Lepton Flavor).

Charm production @ mass threshold

- Around E_{cm} ~ 4.6 GeV , they are produced in pair.
  $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda_c^{\pm}\overline{\Lambda}_c^{\mp}$.



- Typically, two ways to obtain the Λ_c yields:
  - ❖ Single Tag (ST) : Reconstruct only one of the Λ_c-pair.
    - ➡ Larger backgrounds.
    - ➡ Higher efficiencies.
  - ❖ Double Tag (DT): Find both of them.
    - ➡ Smaller backgrounds.
    - ➡ Smaller efficiencies.

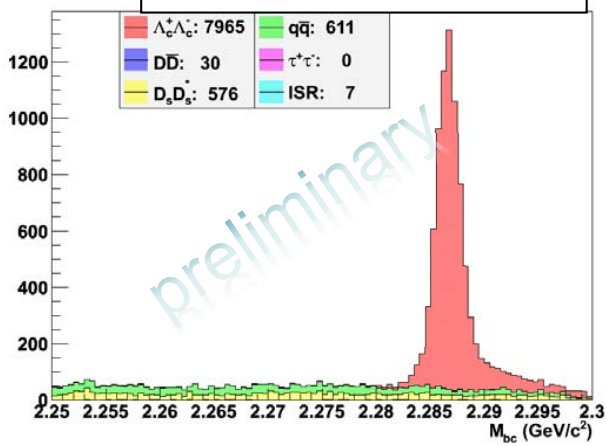
Two popular variables

- Beam-Constrained-Mass; $M_{BC} = \sqrt{(E_{beam}^2 - |\vec{p}_{\Lambda c}|^2)}$

  $\vec{p}_{\Lambda c}$ is a reconstructed Λ_c 3-momentum.

  - Its resolution is dominated by the spread in E_{beam} (i.e., mostly independent of final states of Λ_c decays.
  - The signal has asymmetric shape (longer tail on its high side) due to the ISR effect ($|\vec{p}_{\Lambda c}|$ gets smaller)

A typical ST M_{BC}



- $\Delta E = E_{\Lambda c} - E_{beam}$
  - Almost independent of the measured M_{BC}.

$BF(\Lambda_c^+ \to p\, K^-\, \pi^+)$

PRL 116, 052001 (2016)

- First absolute BF measurement of this golden mode.
- Improved BF measurements of other CF hadronic modes.
- The BFs are extracted via the double-tag technique.
- For instance, for the case of $\Lambda_c^+ \to p\, K^-\, \pi^+$ and $\overline{\Lambda}_c^- \to \overline{\Lambda}\, \pi^-$:

$BF(\Lambda_c^+ \to p\, K^-\, \pi^+)$

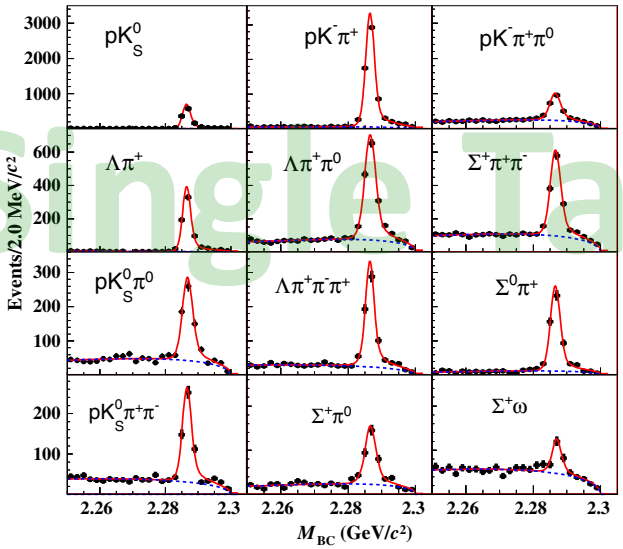
$= N_{DT}/N_{ST} \times \varepsilon(\overline{\Lambda}_c^- \to \overline{\Lambda}\, \pi^-)/\varepsilon(\overline{\Lambda}_c^- \to \overline{\Lambda}\, \pi^- \text{ and } \Lambda_c^+ \to p\, K^-\, \pi^+)$.

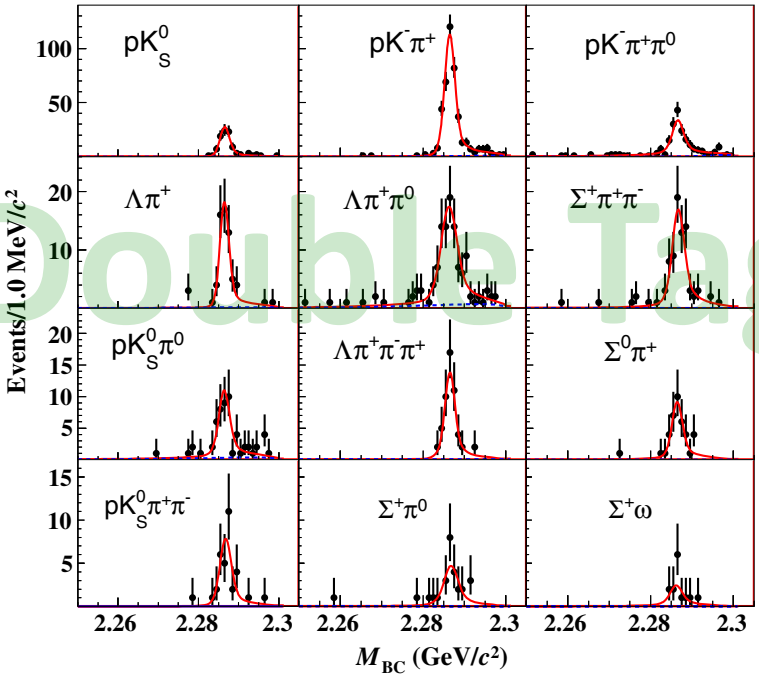
Notice that;

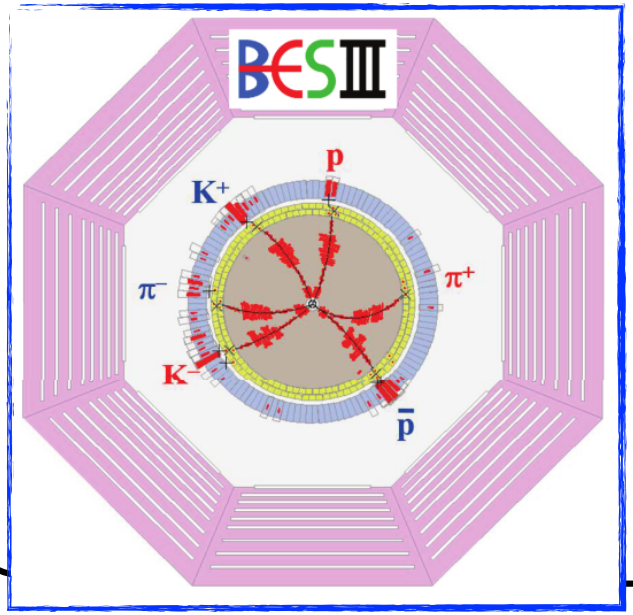
- BF is determined independent of $N_{\Lambda_c\overline{\Lambda}_c}$ and
- The systematic uncertainty due to the reconstruction of $\overline{\Lambda}_c^- \to \overline{\Lambda}\, \pi^-$ tend to be canceled in the ratio.

Extracting N_{ST} and N_{DT}

- Look for 12 different tag modes.







- Very clean event environment!
- In the above DT case, summed over the 12 tag modes
- Simultaneously fit to the all $N_{DT} = N_{\Lambda_c\bar{\Lambda}_c} \times BF_{\bar{\Lambda}_c\to tag} \times BF_{\Lambda_c\to sig} \times \varepsilon_{DT}$, while constraining $N_{\Lambda_c\bar{\Lambda}_c}$, taking into account correlations over modes.
  $N_{\Lambda_c\bar{\Lambda}_c}$ will be a byproduct.

Mode	This work (%)	PDG 2014
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

Belle
$BF(\Lambda_c^+ \to p\, K^-\, \pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$
PRL 113, 042002 (2014)

- $BF(\Lambda_c^+ \to p\, K^-\, \pi^+)$: Consistent? … within ~2σ …
  Hopefully, the agreement would improve further in the near future.
  (more data? new technique?)
- Also obtained $N_{\Lambda_c\bar{\Lambda}_c} = (105.9 \pm 4.8 \pm 0.5) \times 10^3$.
- Other $BF(\Lambda_c^+ \to$ hadrons) are measured with improved precisions.

Observation of $\Lambda_c^+ \to n K_S^0 \pi^+$

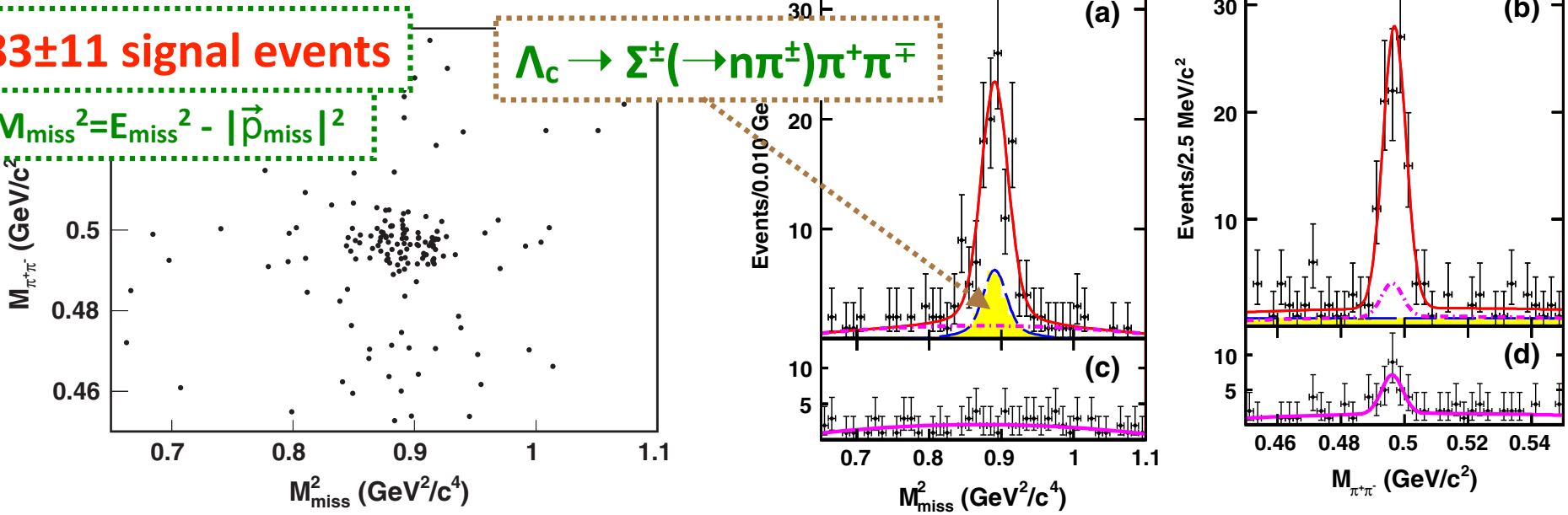
PRL 118, 112001 (2017)

- First direct measurement Λ_c decay involving the neutron in the final state.
- A test of the isospin symmetry.

83±11 signal events

$M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}|^2$

$\Lambda_c \to \Sigma^{\pm}(\to n\pi^{\pm})\pi^+\pi^{\mp}$



$BF(\Lambda_c^+ \to n K_S^0 \pi^+) = (1.82 \pm 0.23 \pm 0.11)\%$

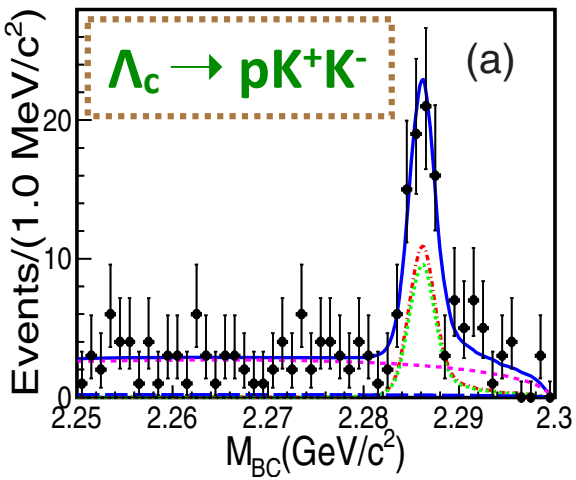
$BF(\Lambda_c^+ \to n K^0 \pi^+)/BF(\Lambda_c^+ \to p K^- \pi^+) = (0.62 \pm 0.09)\%$ (w/ BESIII's meas.)

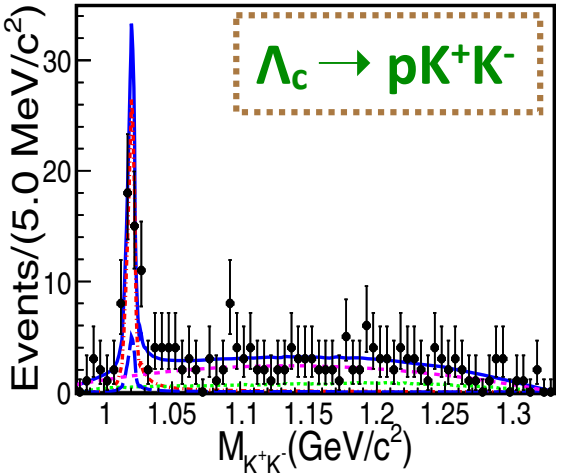
$BF(\Lambda_c^+ \to n K^0 \pi^+)/BF(\Lambda_c^+ \to p K^0 \pi^0) = (0.97 \pm 0.16)\%$ (w/ BESIII's meas.)

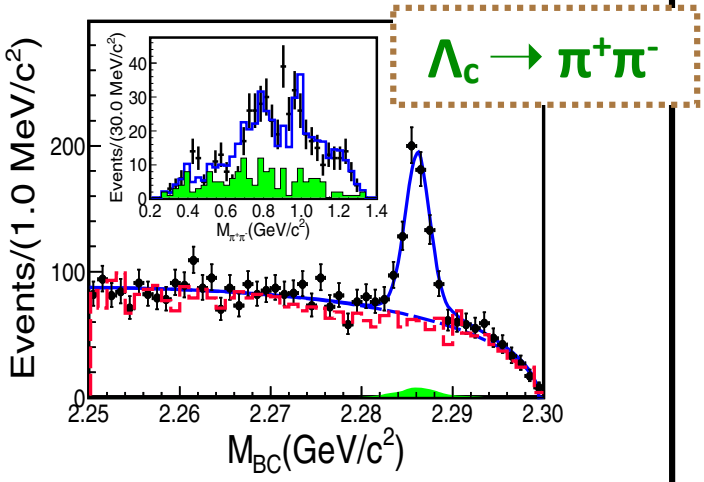
$\Lambda_c^+ \to p\,\pi^+\pi^-$ and $p\,K^+K^-$

PRL 117, 232002 (2016)

- Single Tag method ⇒ relative BF w.r.t. the $pK^-\pi^+$ mode.
- First observation of single Cabibbo-suppressed (SCS) decay of $\Lambda_c^+ \to p\,\pi^+\pi^-$.
- Improved measurements on the SCS decays, $\Lambda_c^+ \to p\phi$ and $\to pK^+K^-_{\text{non-}\phi}$.





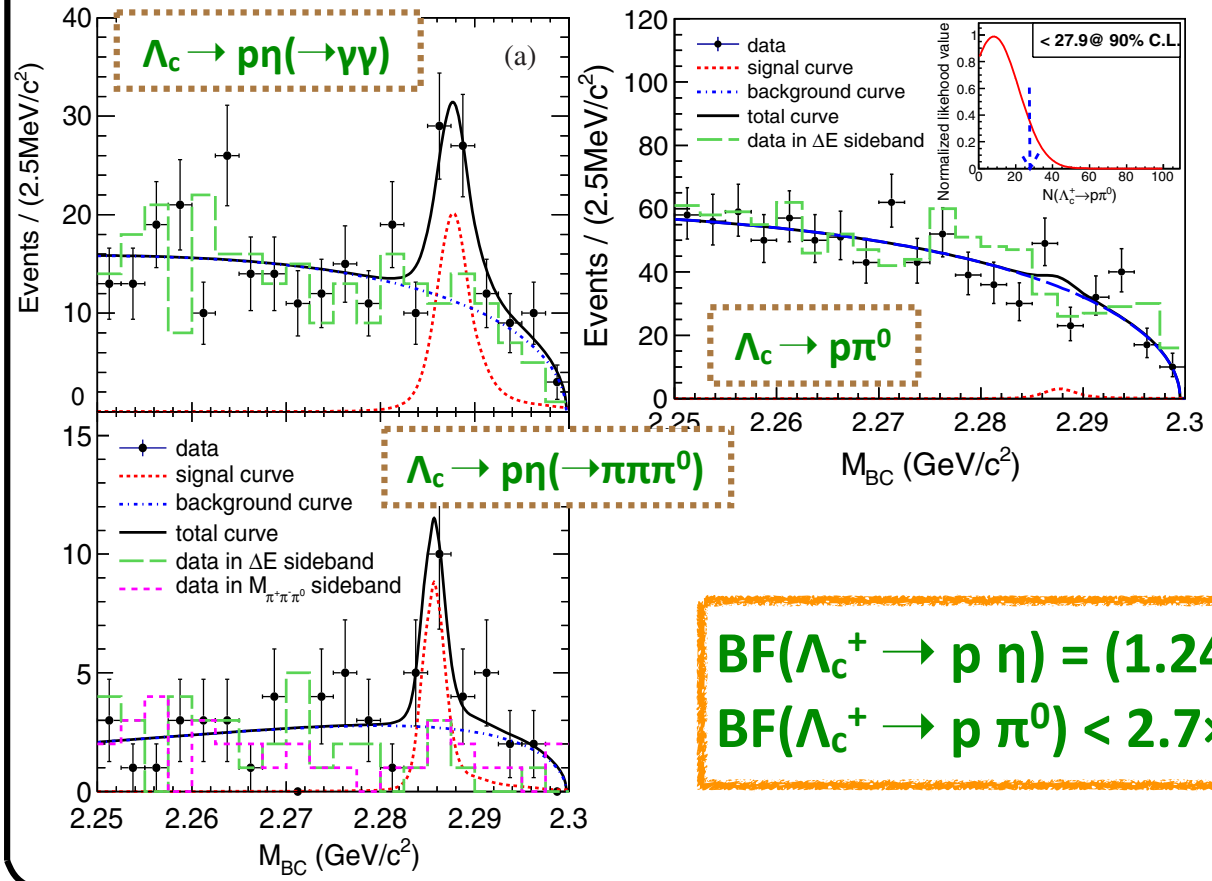


Decay modes	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref}}$ (This work)	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref}}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(6.9 \pm 3.6) \times 10^{-2}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.64 \pm 0.32) \times 10^{-2}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$(7 \pm 2 \pm 2) \times 10^{-3}$
–	$\mathcal{B}_{\text{mode}}$ (This work)	$\mathcal{B}_{\text{mode}}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

$\Lambda_c^+ \to p\,\eta$ and $p\,\pi^0$

PRD 95, 111102(R) (2017)

- First evidence of the SCS decay, $\Lambda_c^+ \to p\,\eta$ (4.2σ stat. significance).
- No signals seen in $\Lambda_c^+ \to p\,\pi^0$.
- Predicted BFs vary under different theoretical models (SU(3) symmetry and FSI).



	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+\to p\pi^0}}{\mathcal{B}_{\Lambda_c^+\to p\eta}}$
BESIII	1.24 ± 0.29	<0.27	<0.24
Sharma *et al.* [3]	$0.2^a(1.7^b)$	0.2	$1.0^a(0.1^b)$
Uppal *et al.* [4]	0.3	0.1–0.2	0.3–0.7
S. L. Chen *et al.* [12]	...	$0.11–0.36^c$	...
Cai-Dian Lü *et al.* [13]	...	0.45	...

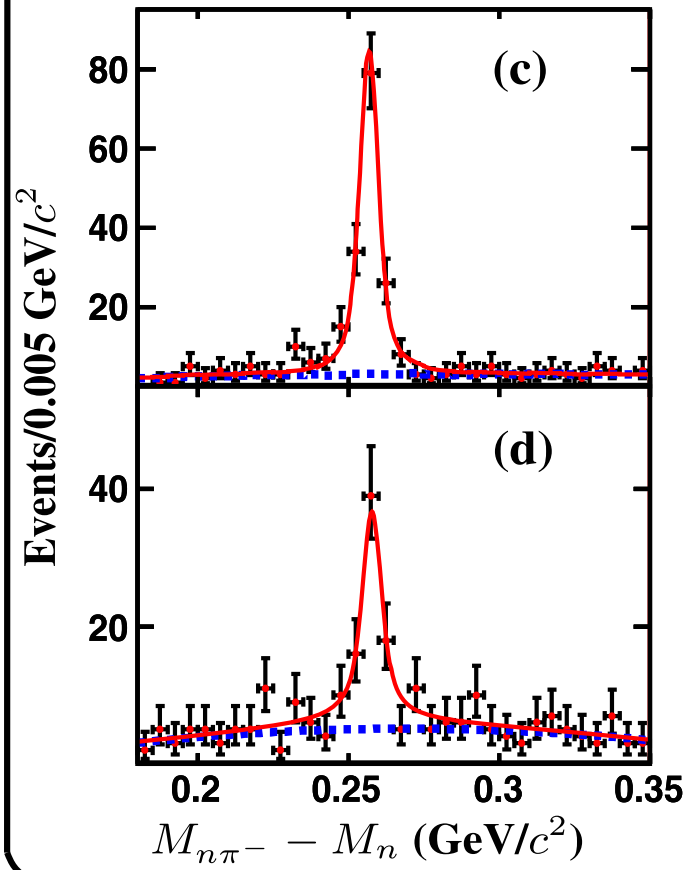
[a]Assumed to have a positive sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[b]Assumed to have a negative sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[c]Calculated relying on different values of parameters b and α.

BF($\Lambda_c^+ \to p\,\eta$) = (1.24±0.28±0.10)×10^{-3}
BF($\Lambda_c^+ \to p\,\pi^0$) < 2.7×10^{-4} @ 90% C.L.

Observation of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$

Recently accepted to PLB

- First observation of CF decay, $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$.
- and improved BF on $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$.
- $\Sigma^- \to n\pi^-$ is reconstructed .



- Fit to $M_{n\pi^-} - M_n$ to extract the signal yields.

$$M_{n\pi^-} = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^+(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+(\pi^0)}|^2}$$

$$M_n = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^+\pi^-(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+\pi^-(\pi^0)}|^2}$$

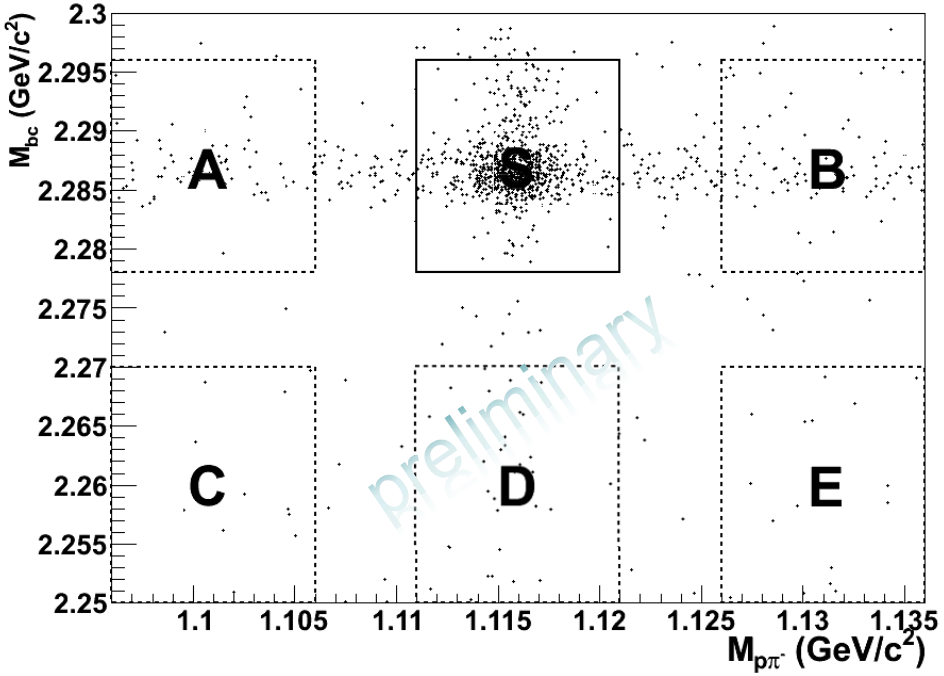
BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$) = (2.11±0.33±0.14)%

BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$) = (1.81±0.17±0.09)%

$\Lambda_c^+ \rightarrow \Lambda + X$

~preliminary result~

- Current PDG : BF($\Lambda_c^+ \rightarrow \Lambda + X$) = (35±11)%
  Large rate, but also with large uncertainty…
- Double tag method: Tagged with two modes; pKπ and pK_S.
- Extract yields from 2D distributions in bins of $p_{p\pi}$ and $|\cos\theta|$, where θ is the polar angle w.r.t. the beam pipe.



- BF($\Lambda_c^+ \rightarrow \Lambda + X$) = (36.98±2.18)%
- Also, looked for;

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} + X)}.$$

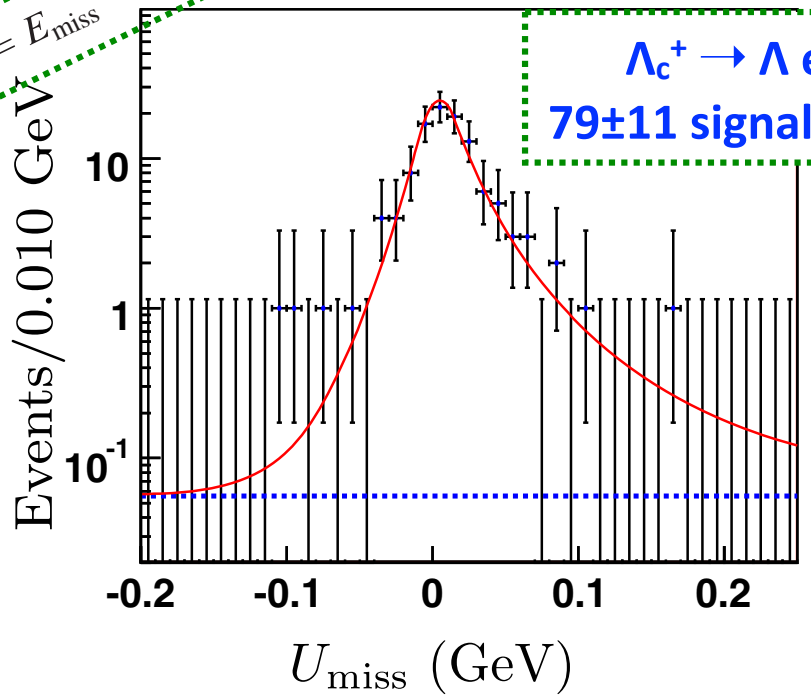
- A_{CP} = +0.02±0.06.

BF($\Lambda_c^+ \to \Lambda\, e^+\, \nu_l$)

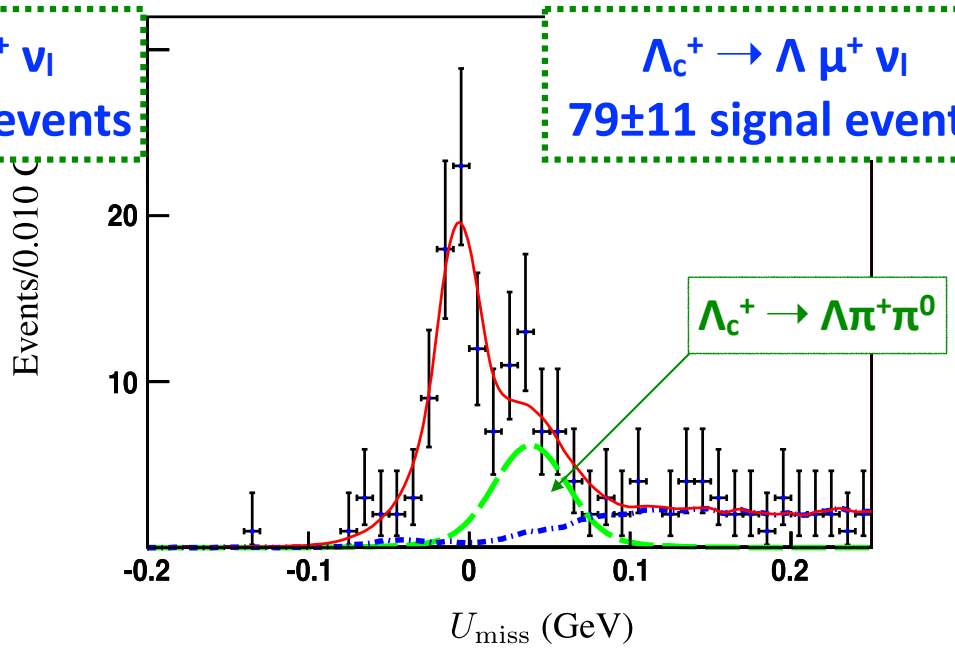
PRL 115, 221805 (2015) and PLB 767, 42 (2017)

- Large rate via the CF transition, $c \to s\, l^+\, \nu_l$.
- First absolute BF measurement!
- First measurement of its muonic mode!

$U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$



$\Lambda_c^+ \to \Lambda\, e^+\, \nu_l$
79±11 signal events



$\Lambda_c^+ \to \Lambda\, \mu^+\, \nu_l$
79±11 signal events

BF($\Lambda_c^+ \to \Lambda\, e^+\, \nu_e$) = (3.63±0.38±0.20)%

- BF($\Lambda_c^+ \to \Lambda\, \mu^+\, \nu_\mu$) = (3.49±0.46±0.27)%
- $\Gamma(\Lambda_c^+ \to \Lambda\, \mu^+\, \nu_\mu)/\Gamma(\Lambda_c^+ \to \Lambda\, e^+\, \nu_e)$ = 0.96±0.16±0.04

Summary

- BESIII has improved various Λ_c BFs significantly and made measurements on some new decay modes as well based on ~0.2M Λ_c.

- Will continue to study on Λ_c decays (other hadronic/semi-leptonic/rare decays).

- BESIII will keep collecting data in the next ~ decade.

- The current plan is to accumulate 1M Λ_c in total (along with 50M D^0/50M D^+/15M D_s/10B J/ψ).